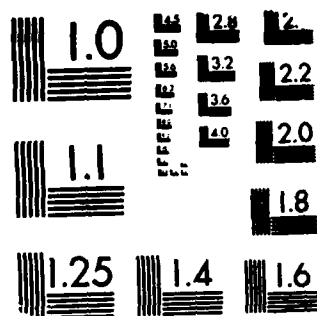END

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Center for Night Vision
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AN OPTICAL PREAMPLIFIER
FOR DETECTION OF CO_2
LASER RADIATION

by
Jay A. Fox
and
Cynthia R. Gautier

January 1988

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A tunable, low pressure CO_2, transverse discharge system is described in order to test an optical preamplifier that can provide gain to incoming laser radiation in the 9 - 11μm range without adding detectable noise. Especially high gains were observed on strong laser lines such as 10P20, suggesting the potential use of the preamplifier in certain applications including long-distance rangefinding.

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i

PREFACE

This report describes the testing of an optical preamplifier designed to improve the signal-to-noise ratio of the direct detection of CO_2 laser radiation. More specifically, we describe a tunable, CO_2 low pressure, transverse discharge device which can provide gain to any incoming laser radiation in the 9 to 11 μm band without adding detectable noise. The measured gain is present as a function of preamplified-applied voltage and gas pressure as well as wavelength.

Currently, there are two practical methods of detecting relatively weak CO_2 laser radiation—*direct* and *heterodyne* detection, each having advantages and disadvantages. The intrinsic advantage of direct detection is that it is relatively simple and does not involve any instrumentation other than the detector itself. Unfortunately, detector noise presents a formidable problem for some lidar applications; thus, in order to provide sufficient signal-to-noise ratios, either the transmitter energy must be increased or the collecting aperture of the receiver must be expanded, or both. This results in an increased system size and weight, which is undesirable (and perhaps unacceptable) for certain military applications.

On the other hand, heterodyne detection systems are 20 - 30dB more sensitive than direct detection systems of equal output pulse energy because their practical noise limit is relatively close to photon noise. Thus, coherent lidars utilizing heterodyne detection offer the promise of being lighter and more compact than direct detection systems with comparable sensitivity. However, this advantage is achieved at the cost of added complexity. Generally, another laser must be added as the local oscillator and both lasers must be frequency stabilized. In addition, coherent speckle effects are much more pronounced for a heterodyne system and considerable signal averaging is required to increase the signal-to-noise ratio to acceptable levels. Since this must be done in a short time relative to changes in the target being illuminated, even a coherent system might have serious operational limits.

There is a third possibility for increasing detection sensitivity. If the amount of incoming radiation could be increased by means of an optical preamplifier placed in front of the detector without a corresponding increase in noise, then the probability of detection would rise. This is not a new concept in that it has been described in the past.[1,2,3] However, although the most successful CO_2 device reported did achieve respectable gains (39 dB), the small signal gain per unit length was so small ($\approx$ 1% cm^{-1}) that a total path length of 10 meters was required to achieve this performance. Although multi-passing the beam is a possibility, the complexity of a system utilizing this many passes is undesirable for practical usage. The major problem with previous systems was that they utilized longitudinal, low pressure, CW discharges which tended to have low gain and were rather non-uniform. Clearly, one possibility is to utilize the discharge of a self-sustained TEA-type laser. This device typically has gains of more than 3% cm^{-1} and, in fact, has even been reported to have gains of twice that amount.[4] However, the useful gain of such devices lasts only 1 to 2 microseconds and is typically so peaked, that in order to have reproducible, reliable results, the preamplifier would have to be fired at precisely the right time corresponding to the arrival of the pulse to

be detected. Because this time factor is unknown in most operational scenarios, high pressure discharges are not useful for optical preamplifiers. Even if this were not the case, the large volumes needed for multi-passing the detected beam would require great inputs of energy into the discharge, creating problems of high voltage arcing, non-uniformity of the discharge, and greater size and weight of the pulse forming networks.

Recently, a fourth possible candidate for the optical preamplifier has emerged. A commercial laser vendor (Pulse Systems, Inc.) has utilized a patented method for preionization of a CO_2 lasing mixture to make a large, uniform transverse discharge possible at relatively low (20 to 40 torr) pressures. This approach has a number of potential benefits which make it a viable candidate for the optical preamplifier. For example, the low pressure means that the useful optical gain will continue for perhaps more than 100 μsec, thereby removing the necessity of precisely knowing the arrival time of the radiation to be detected. In addition, it is not necessary at these pressures to use the high voltages commonly associated with atmospheric pressure discharges (20 to 40 kV); instead, only about 1 kV is needed. This not only means that all the usual arcing and corona problems associated with high voltage networks/power supplies can be avoided, but also that the discharge voltages can be switched by solid state components. This eliminates the EMI and reliability problems associated with sparks gaps and the power consumption/thermal problems associated with thyratrons. Additionally, the manufacturer claims a very high gain ($\approx$ 4% cm^{-1}) for this type discharge, which implies that substantial increases in signal levels can be achieved in comparatively short cavity lengths. Because of the potential utility of this device as an optical preamplifier, it was decided to experimentally investigate one of these units. This report presents data that will permit the evaluation of an optical preamplifier for potential Army use, such as in lidar systems designed for chemical detection, rangefinding, obstacle avoidance, or aerosol monitoring. It includes the setup, procedures, discussion of results, and conclusions.

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TABLE OF CONTENTS

SECTION I. EXPERIMENTAL SET-UP AND PROCEDURE

Figure 1 schematically illustrates the arrangement of the apparatus. The gain measurements were made using a tunable, water-cooled, CW CO_2 laser (Line Lite Corporation, Model 950). The laser produced more than 5 watts on the 10P20 spectral line, and could be grating tuned through 55 lines in the 10 μm ($00°1$ - $10°0$) band and the 9 μm ($00°1$ - $02°0$) band. In addition, it could be tuned to line center by means of a piezoelectric transducer. After warmup, the laser was quite stable in ouput power, and generally corresponded to the manufacturer's claim of 5% long term stability (hours), and 0.3% short term stability (minutes). Claimed frequency stability was <5 MHz (hours) and <50 KHz (0.1 seconds). This is not directly measured, but preamplifier performance verified that this laser was, in fact, very stable. A movable beamsplitter was used with a spectrum analyzer (Optical Engineering, Inc., Model 16A) to determine the lasing transition, and then the output pcwer was reduced by means of a polarizing attenuator. The beam was then chopped mechanically and further reduced in intensity by means of coated ZnSe partial reflectors. After passing through the preamplifier, the beam was directed through an aperture to a grating, then focused by a lens onto a photovoltaic HgCdTe detector. The chopper also provided a reference signal to the lock-in amplifier (Princeton Applied Research, Model 128A) which transferred the output of the detector to either a digital voltmeter or an oscilloscope. The preamplifier itself is rectangular in shape and has dimensions of 22 cm high x 19 cm wide, and 56 cm long. The active discharge has dimensions of approximately 3 cm high, 1.8 cm wide, and 28.5 cm long. Incoming radiation makes seven passes through the gain region and the amplified beam exits through a circular aperture approximately 1.8 cm in diameter. The preamplifier is a flowing gas system with a flow rate of approximately 0.3 SCFH, which is controlled by a flow restriction in the vacuum line. According to the manufacturer, the device can operate with a wide range of gas mixtures, including CO_2 and atmospheric air. Although this claim was not verified, the factory-recommended high gain mixture of $He:CO_2:N_2:CO = 65:18:15:2$ was used. For most of the tests, the preamplifier was operated with a pressure of about 27 torr. However, as shown in a later section, this pressure could be changed by substantial increments.

The typical procedure for making gain measurements is as follows:

- Tune the Line Lite laser to the desired wavelength and adjust it to line center.

- Adjust the external grating to the appropriate angle for that wavelength and reduce the input power to a value P_{in1} as read on the digital meter.

- Slip the calibrated attenuator A_2 (transmitting a fraction f of the incoming beam) into place so that the power entering the preamplifier is $P_{in} = fP_{in1}$, a value previously determined to be below the saturation level of the preamplifier.

1

- Measure the amplified output power from the stored oscilloscope trace and calculate the gain to be the ratio of the output to the input power.

The estimated error in the accuracy of the gain measurements is a total of 10%, with the largest contribution coming from the value of transmission for the attenuator.
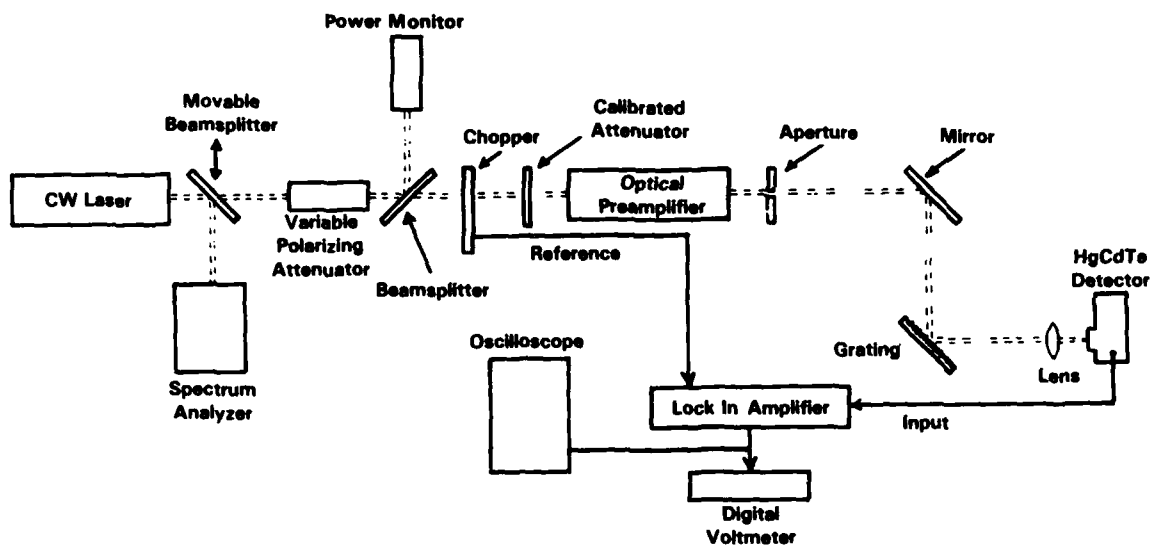
Figure 1. Schematic diagram of the apparatus

SECTION II. EXPERIMENTAL RESULTS

SMALL SIGNAL MEASUREMENTS

It is well-known that if a lasing medium is placed in an optical cavity, any gain which occurs will be a function of intensity and eventually, when that intensity gets large enough, saturation occurs. Ordinarily, the saturation intensity is an important parameter for an optical amplifier, because it is directly related to the maximum energy that can be extracted from the excited medium. That is,

$$I_{out} = I_{in} + (\alpha\ I_s)\ L \qquad\qquad [1]$$

where I_{out} and I_{in} are the output and input intensities into an optical amplifier of gain length L, and $\alpha\ I_s$ is the product of the so-called small signal gain and the saturation intensity. However, in almost all operational situations under which the optical preamplifier will be operated, the small signal condition will prevail. That is, $I_{out}/I_s << 1$, and the output intensity will be related to the input by

$$I_{out} = I_{in} \exp(\alpha\ L). \qquad\qquad [2]$$

All gain measurements contained in this report are for the small signal condition. Experimentally, this was determined by decreasing the input power until a constant value of gain was obtained. For example, see Figure 2 where it can be seen that as the level of the input signal (10P(20) line) decreases from about 50 μw to approximately 3 μw, the gain increases linearly and eventually reaches a maximum level at about 1 μw. This then was small signal threshold point and thus the onset of the region of maximum gain.

Since this 1 μw power is still larger than power levels anticipated in practical usage, all gain measurements reported herein were determined with inputs less than this amount.

GAIN DEPENDENCE ON WAVELENGTH

For some of the possible applications of the preamplifier, it will be necessary to amplify radiation other than that corresponding to the strong 10P(20) transition. For example, for certain chemical detection uses, it will be necessary to access weak gain lines such as 9P(36) or even 9P(40). For that reason, it is important to determine the spectral response of the preamplifier. This portion deals with those measurements taken to achieve this result.
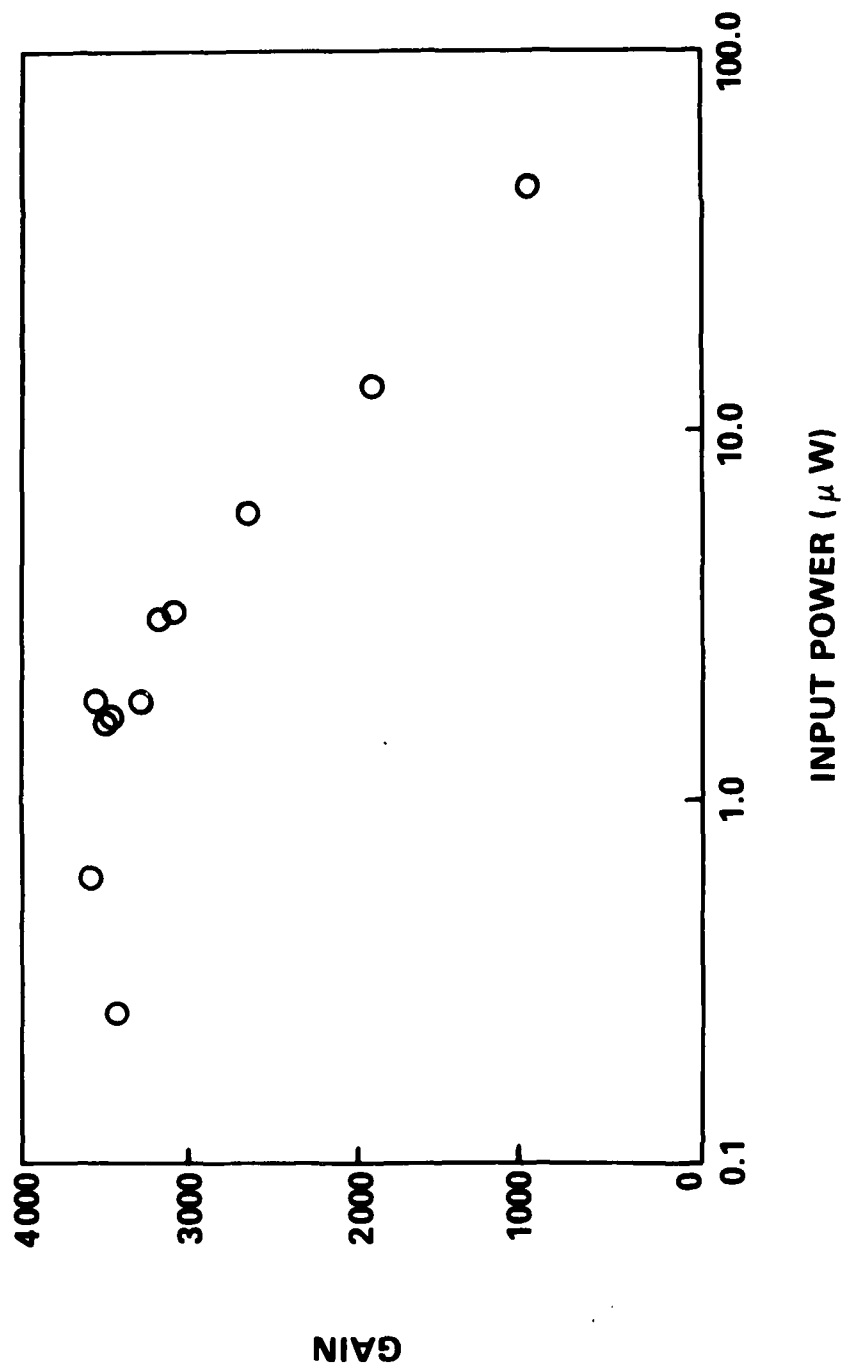
Figure 2. Gain saturation with increasing input power. The maximum gain occurs with inputs of less than approximately 1×10^{-6} watts.

4

There were, however, several problems that had to be overcome. First, the input power had to be reduced to very small values in order to avoid saturation effects (at least for the stronger transitions). However, this meant using input levels that were so low they were lost in the noise of the system without even firing the preamplifier. Thus, the technique adopted for achieving the desired input was to reduce this signal to a value still readable above the noise (but too large to use directly), and then to further reduce it to the desired level by means of a calibrated attenuator. The attenuators chosen were coated ZnSe partially transmitting laser mirrors. Because of the low levels of input powers required, the attenuators typically transmitted only a small portion of the incident radiation ($\approx 0.1 - 3\%$). This created a problem in that the relatively thick, multi-layered attenuator coatings proved to be quite angle and position sensitive. Thus, considerable error could be induced if the filters were not repositioned in precisely the same location each time a measurement was taken. This condition was remedied by means of an optical mount positioned on a calibrated sliding stage that allowed translational reproducibility with no measurable angular deviations.

A second problem surfaced with respect to the filters. It was discovered that the filters exhibited a strong wavelength dependence over the 9 to 11 μm spectrum. This, of course, was not anticipated in view of the thickness of the applied coatings and the many layers required in order to reduce the transmission to such low values. However, the data is presented for one of the attenuators as an indicator of how severe the transmission correction must be in certain portions of the spectrum (Figure 3). This curve was obtained with a Perkin-Elmer Model 983G spectrophotometer with a resolution of 0.5 cm^{-1} and it was the source of the attenuator values used for the gain measurements.

A third problem encountered was amplified spontaneous emission (ASE), which refers to the noise radiation emitted spontaneously by the upper laser population. Following the treatment given in Yariv,[5] it is possible to show that the ASE power per line collected by the detector is

$$P_L = \frac{A_a A_d}{F^2} \; \Phi_L G_L \; (S\delta f/\lambda^2) \; hf \qquad [3]$$

where A_a is the clear viewing area of a lens with focal length F used to focus the ASE onto a detector of area A_d, and G_L is the amplifier gain on line L, the frequency of emission is f, Planck's constant is h, δf is the line width, λ is the line center wavelength for the laser transition on line L, S is a constant equal to 1 if a polarizer is used in front of the detector and equal to 2 otherwise.
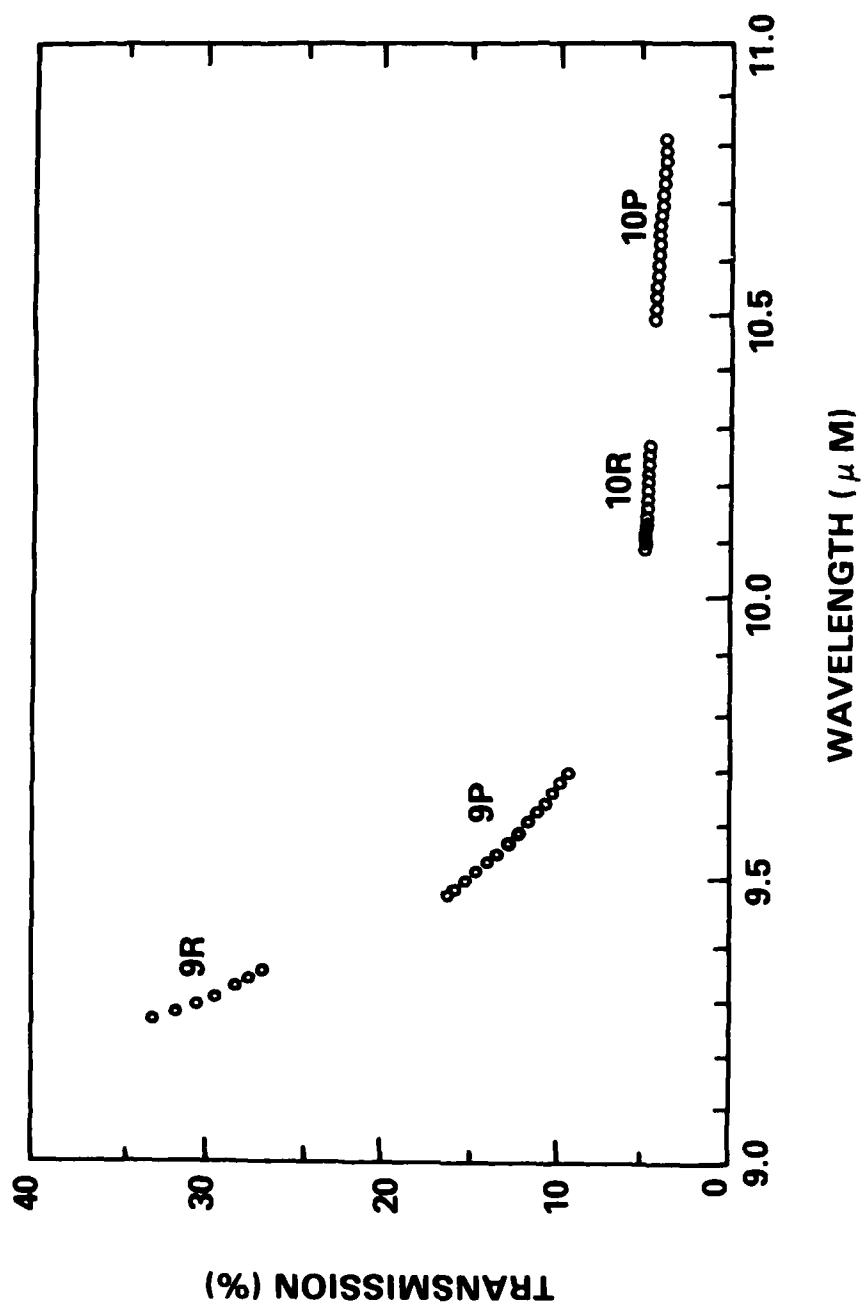
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Figure 3. Spectral response of a high reflectivity filter

6

The term Φ_L is given by

$$\Phi_L = \left[\frac{N_2}{N_2 - N_1(g_2/g_1)} \right] \left[\frac{G_L - 1}{G_L} \right] \qquad [4]$$

where N_2 and N_1 are the population densities for the upper and lower levels of line L with degeneracies g_2 and g_1, respectively, and G_L is the amplifier gain on line L. The total power P on the detector due to ASE is simply the sum of the individual components, or

$$P = \sum_L P_L. \qquad [5]$$

The time evolution of the ASE follows the gain of the amplifier and is so low-level that it was not noticeable until measurements of low gain lines were attempted. Figure 4 depicts an actual gain measurement of the 10P6 line. Note that the ASE is a significant fraction of the observed gain signal and would result in substantial error in the measurement if not accounted for. In practice, there are a few ways in which this problem can be alleviated. Since the typical signals of interest for most applications are of much shorter duration than that of the ASE, the output could be frequency filtered to eliminate that contribution. McLellan[6] has suggested that, if this is not practical, the signal from a second detector element which views the ASE but not the signal of interest can be subtracted from the first detector signal, thus eliminating the ASE contribution. Another possibility depends on the fact that the ASE signal is reproducible and therefore could be eliminated by computer processing of the return. However, there is a simpler approach that we have chosen to use. By placing a grating in the detection path and tuning it so that only the wavelength of interest is viewed, the total ASE observed power is dramatically decreased and, in fact, becomes so small that it is unobservable within the general noise level of the system. Therefore, we estimate that the presence of single-line ASE causes no error in gain measurements and would not create a problem in viewing a typical signal for most applications.

A fourth problem arose when too much input power was applied to the preamplifier. The unit started to lase on its own (self-lasing) because the gain was so high. This gave rise to a huge signal which temporarily saturated the detector (Figure 5), evidently caused by some off-axis feedback within the amplifier and eliminated by a circular aperture of approximately 8mm diameter placed between the preamplifier and the grating (see Figure 1).
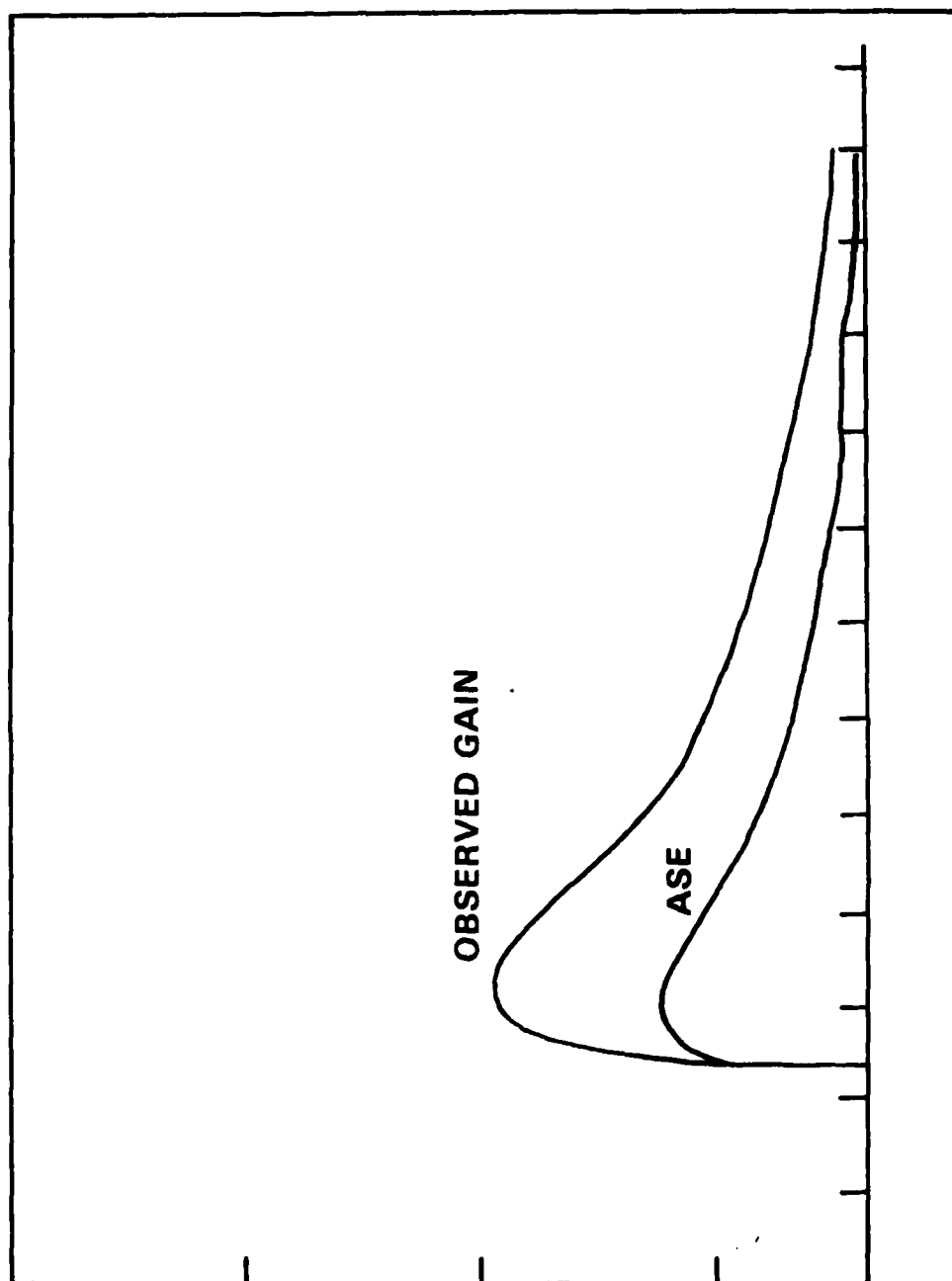
Figure 4. Observed gain pulse for 10P6 radiation (50 μsec/div).
The apparent gain is substantially increased by the
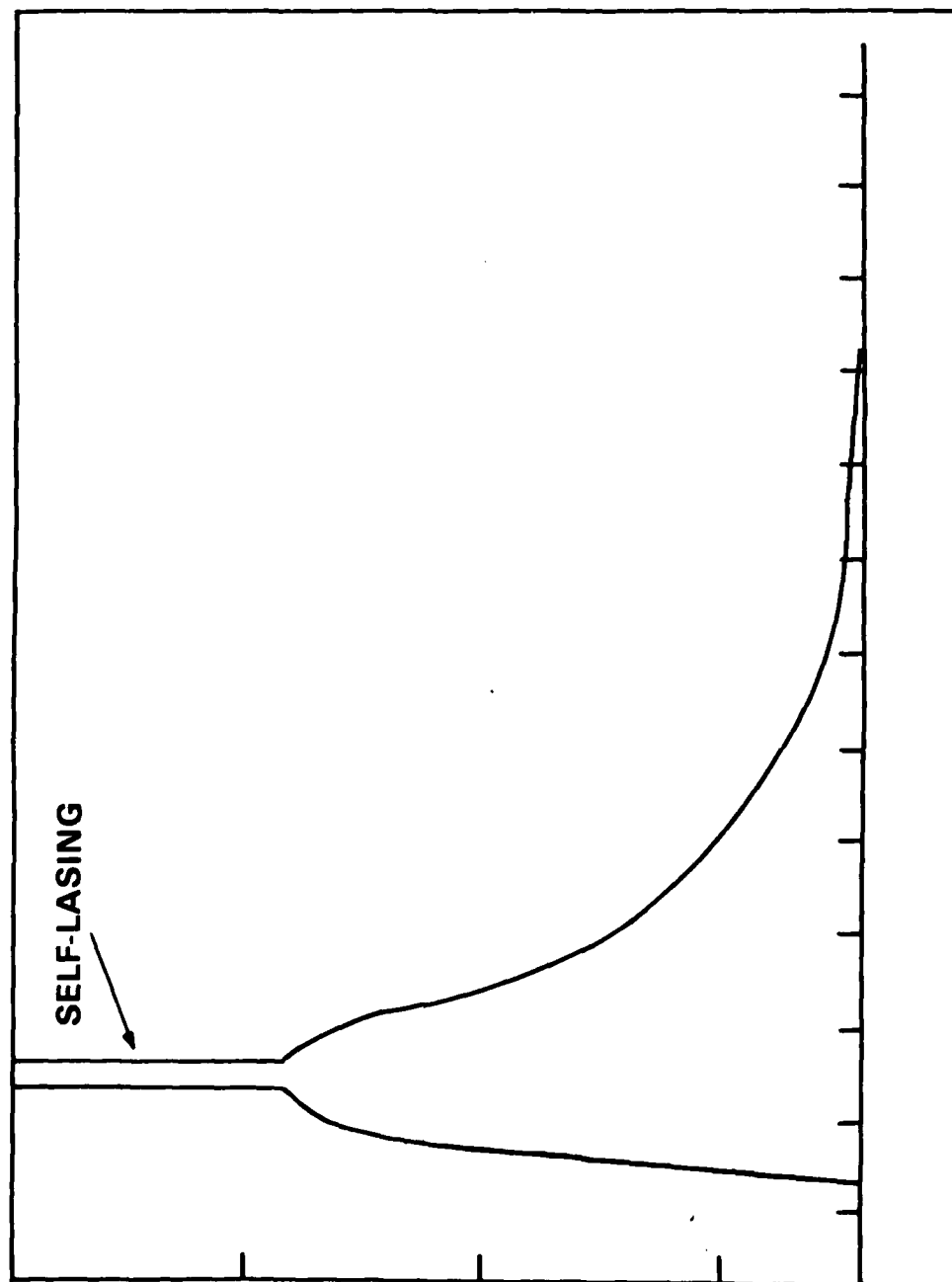amplified spontaneous emission (ASE).

8

Figure 5. Self-lasing occurring during a 9R22 gain pulse (50 μsec/div)

SELF-LASING

9

With self-lasing and ASE suppressed, the gain shape and width were reproducible from shot to shot as long as the discharge did not contain any "streamers" or arcs, a condition that prevailed under most operating conditions unless the preamplifier was pumped with too much input energy. The peak height did not change by more than 10% from shot to shot, and a significant portion of this was due to the change in input power from the CW laser. It is not possible to be more precise about this since the actual CW input at the time of the gain pulse could not be monitored. The full width at half maximum (FWHM) of the gain varied as a function of wavelength, but was typically ≈ 100 μsec while the entire length was about 450 μsec. Figure 6 shows how the FWHM varied with wavelength for the 10P and 9P transitions. The pulse widths ranged from 90 to 170 μsec, with the shorter times occurring for the transitions to the lower J-levels.

The wavelength response of the preamplifier was measured by the technique outlined earlier and the results are shown in Figure 7. The operating pressure was 27 torr. Note the wide range of measured gains, with values as great as about 2,800 (4% cm^{-1}) for the 10P20 transition, to a value as low as 11 (1.2% cm^{-1}) for the 10P40 line. It should be noted that there was no observable increase in the noise level during the firing of the preamplifier. Thus, the gains were real increases in the signal to noise levels. As expected, the gain proved to be dependent on both the operating pressure and the voltage applied to the discharge.

Figures 8 and 9 show these results for both a strong gain line (10P20) and for a weak gain line (9P36), respectively. Gains of more than 5,000 were measured for the 10P20 transition, while the weaker transition gain could be increased to slightly more than 40. At the highest values of applied voltage, discharge instabilities sometimes occurred and arcing was observed. The gain at 10P20 corresponded to the manufacturer's claim of greater than 4% cm^{-1}.
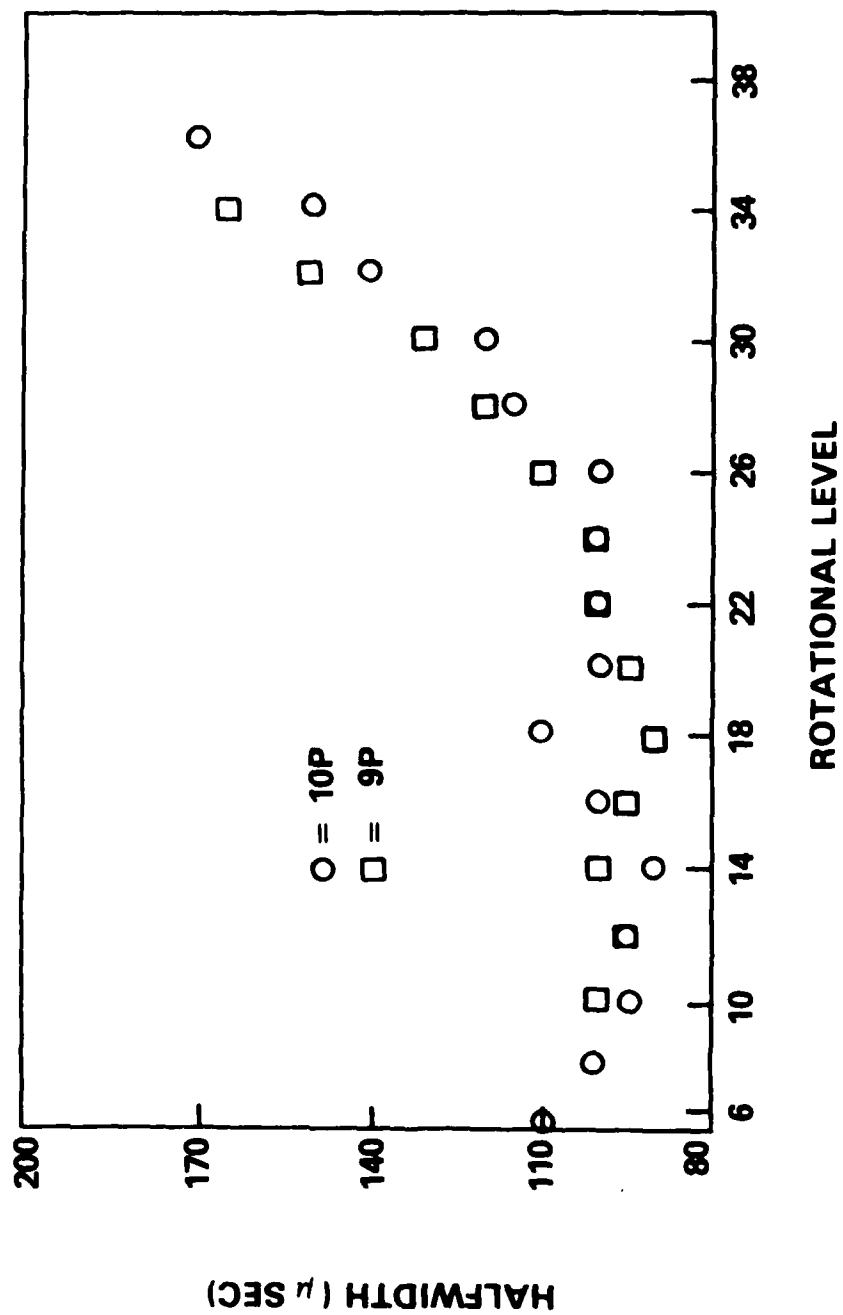
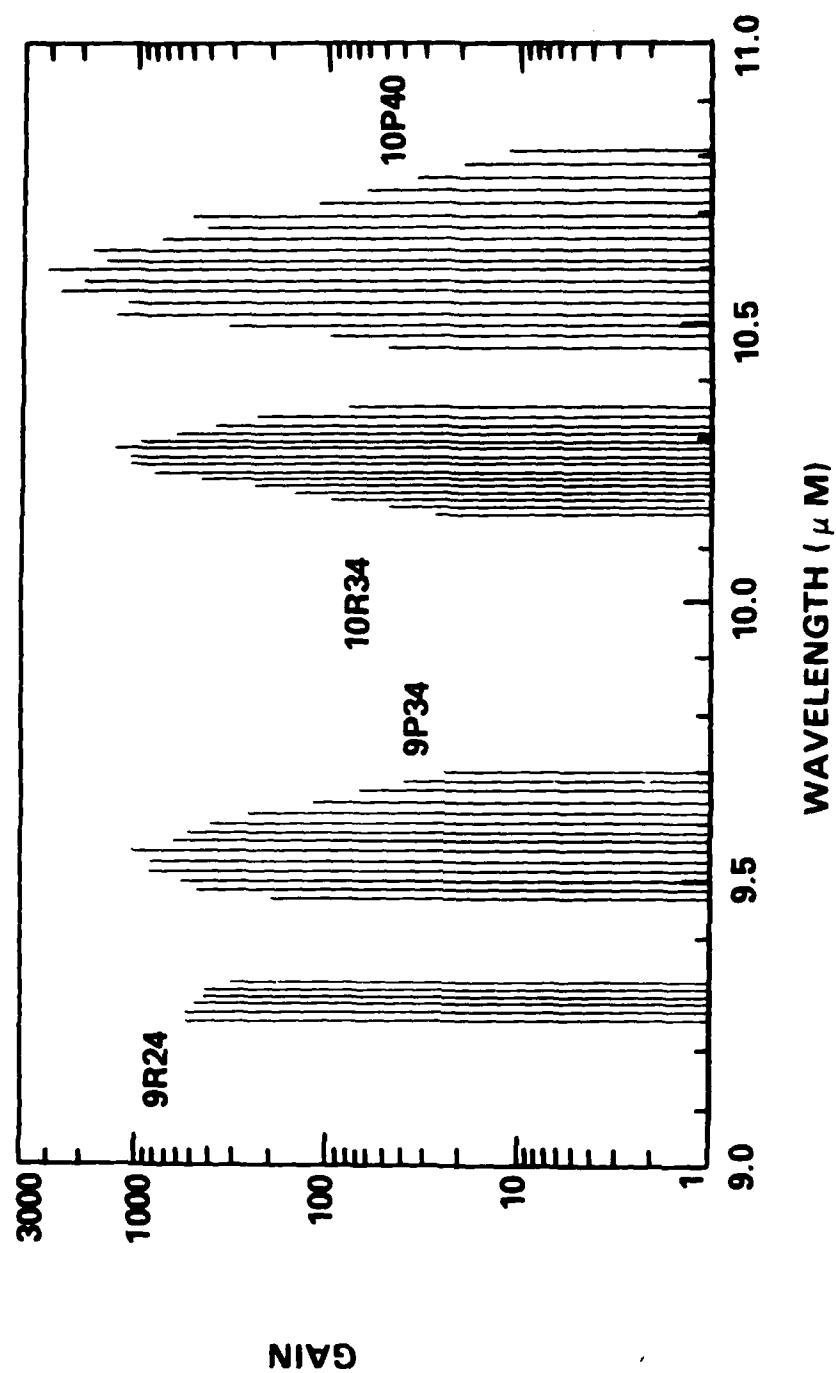Figure 6. Full width at half maximum of gain pulses as a function of wavelength

11

Figure 7. Wavelength response of the optical preamplifier (1,200 volts applied and a pressure of 27 (torr)
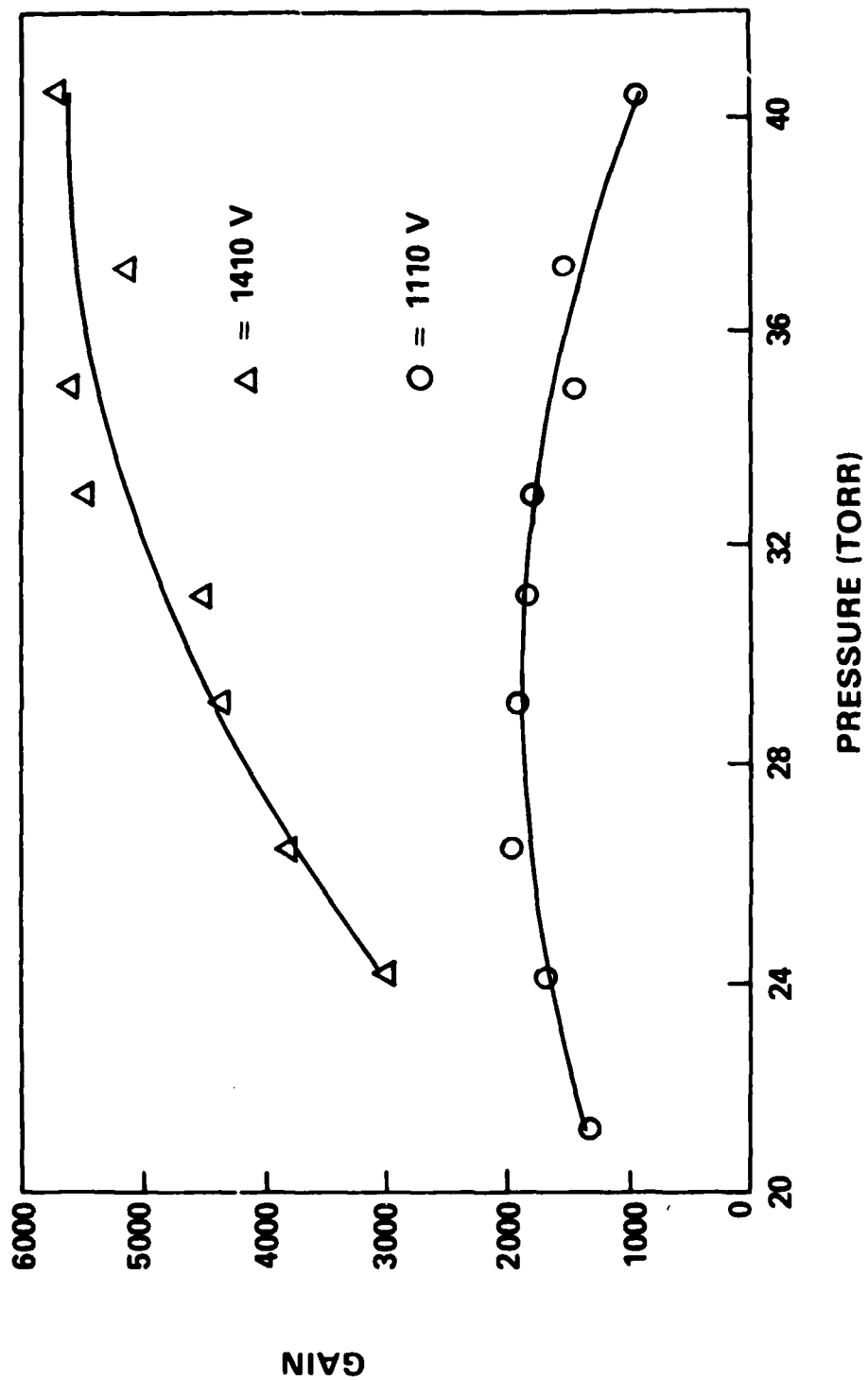
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Figure 8. Variation of gain with pressure and applied voltage for 10P20 radiation
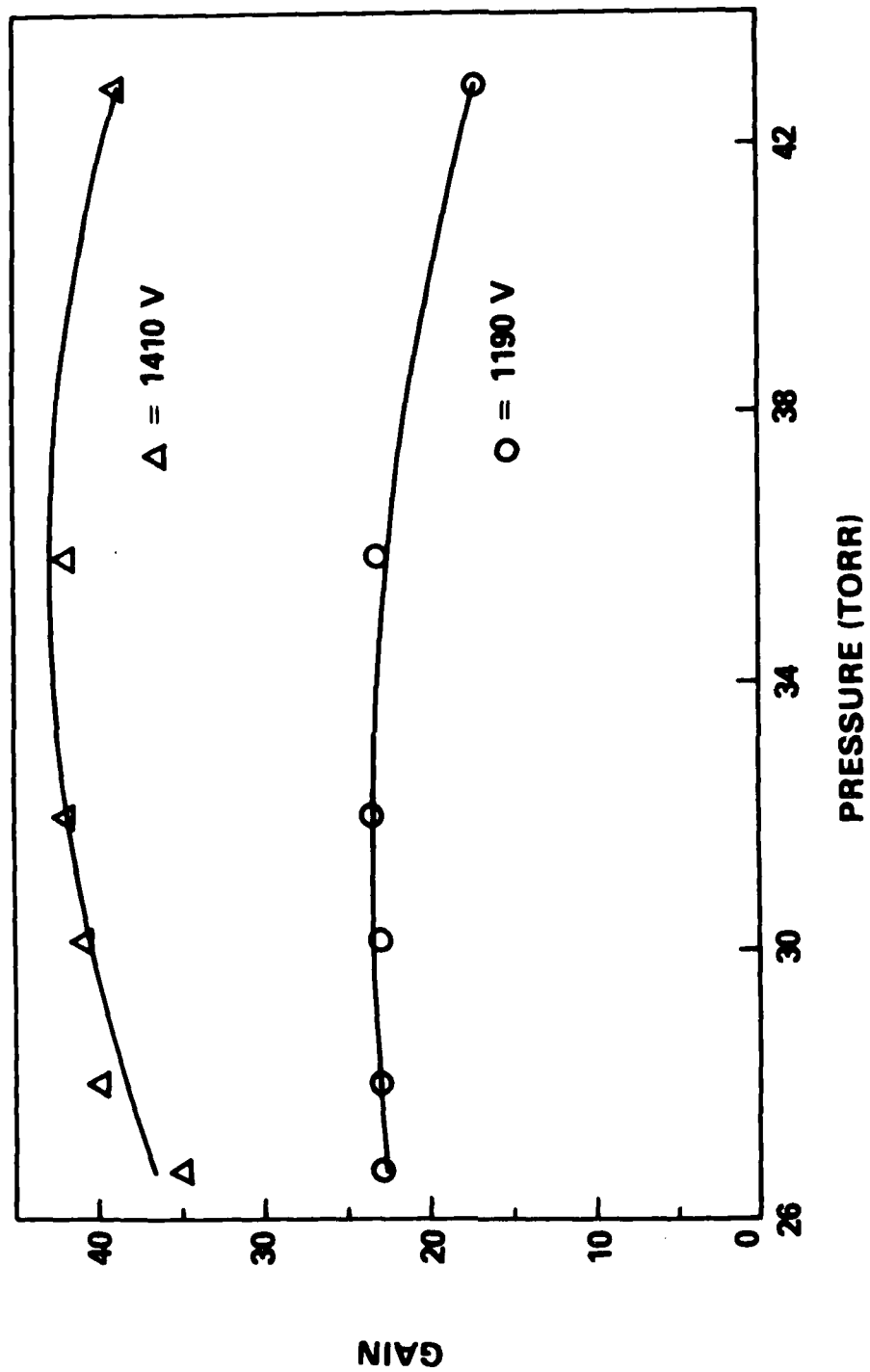
13

Figure 9. Variation of gain with pressure and applied voltage for 9P36 radiation

14

SECTION III. DISCUSSION

It has been shown that an optical preamplifier is capable of achieving significant small–signal gains ($\approx 4\%$ cm $^{-1}$) for strong transitions. Therefore, such a device might be useful for long-range rangefinders, aerosol sensors, or any application that does not require operation at the very weak gain transitions. Weighing against the use of this device is the necessity of operating the transmitter of any laser system in such a manner as to be within the gain curve of this low pressure discharge. This would be a problem for existing TEA lasers, for example, since their gain has a bandwidth 50 to 100 times larger than that of the optical preamplifier. Therefore, if the transmitter is not locked on line center, considerable jitter in the output will be seen. In fact, it has been observed by others[7] that many times no amplification at all is observed, while at other times the full value is obtained. Clearly, this is an unsatisfactory situation for most applications. There are, however, several possible means of ameliorating this condition.

The amplifier could be operated at higher pressures, thus increasing the bandwidth. For example, changing the pressure from 20 torr to 120 torr is expected to increase the bandwidth at 90% of maximum gain from 50 MHz to 220 MHz. This should decrease the amplified signal jitter considerably, and could thereby increase the utility of the preamplifier, especially for devices such as rangefinders where the actual magnitude of the signal is not important as long as it exceeds a certain threshold. However, the pressure probably cannot be profitably increased much beyond 100 to 120 torr. It is much more difficult to obtain such a uniform discharge at very high pressures, and the gain would probably be difficult to maintain. Moreover, since higher and higher voltages would be required to pump the gas at greater pressures, an intrinsic advantage of the preamplifier, i.e. low voltage, noiseless, spark gap free operation, would be lost. Finally, as the pressure is increased, the spontaneous emission noise increases due to the pressure broadening of the laser line.

Another method of solving the bandwidth problem is to lock the laser transmitter to line center. While this would certainly work, it has the disadvantage of adding complexity and additional hardware to a lidar which already is being complicated by the addition of the preamplifier. In fact, one may argue that the level of complexity and potential problems approach that of a heterodyne system. On the other hand, because speckle averaging will probably not be a serious problem with the use of the preamplifier, there is still the advantage that the length of time needed to remain on target would be much less than that required by coherent detection systems.

Next, there is the possibility of using a comparatively low pressure CW transmitter and electro-optically Q-switching it. This has the advantage of the intrinsic longer life of the laser compared with TEA lasers, for example. There might even be a size advantage for the CW-based system since this type laser is typically two to three times more efficient

than a TEA laser. However, this remains to be shown, since the Q-switching mechanism will introduce losses that will at least partially negate the efficiency advantage. However, the real problem with this approach is that a reasonably sized (say 10 watts on lines of interest) low pressure CW system could probably produce only about 1 kW peak power, or a factor of about 500 to 1,000 less than that emanating from typical TEA lasers. Thus, a considerable amount of signal averaging would be needed to produce equivalent signal to noise ratios. For most if not all scenarios, this would be an unacceptable restriction. Thus, this is probably not the approach of choice. There is also a possibility that a pulsed, higher pressure waveguide laser could be Q-switched, and thereby generate more peak power than an CW laser of equal average power; however, this also remains to be demonstrated.

Finally, there is the problem of the comparatively weak gain lines. For example, as we have seen, the gain on the 9P36 line was only 40 with the current system. For some applications, such as chemical sensing, we feel that this amount of gain would not be sufficient to warrant adding the complication of an optical preamplifier to a conventional lidar system. The amount of gain obtained by at least two more passes through the cavity would be needed to make the use of an optical preamplifier feasible for this application (that is, a total gain of about 100). With this modification, however, self-lasing could increase to such an extent that considerable internal aperturing and an internal grating might be required.

SECTION IV. CONCLUSIONS

In conclusion, we have tested an optical preamplifier and found that it is possible to achieve high gains on strong laser lines such as 10P20. These gains would be useful in applications such as long distance rangefinders. For applications using weak laser lines, although no fundamental problems stand in the way, further development that would increase gain would be necessary. In any application, the practicality of this device is dependent on resolving the issue of the lack of bandwidth compatibility with typical TEA lasers. As demonstrated, operation of the preamplifier at higher pressures may help for some applications, provided that some type of transmitter frequency stabilization is effected.

FOOTNOTES

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18

20

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